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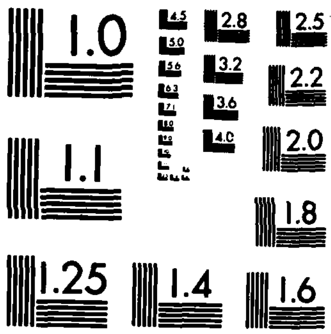

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5 JANUARY 1978

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COPPER AND TANTALUM ROOM TEMPERATURE YIELD STRENGTH CURVES

5 JANUARY 1978

JOHN J OSBORN
Lt Col USAF

WILLIAM H COOK

TABLE OF CONTENTS

SECTION I

SUMMARY

This report presents calculational results for cylinder impact tests and self forging fragment tests for several copper and tantalum specimens. The calculations provide estimates of room temperature yield strength for these specimens.

The results are summarized below.

SPECIMEN	YIELD STRENGTH
Electrolytic Tough Pitch (ETP) Copper in annealed 4.5 inch diameter bar	Initial Yield = 1.2 kilobars Tangent modulus = 8.5 kilobars Maximum yield = 4.5 kilobars
ETP Copper in 1.0 and 0.75 inch diameter bars	Initial yield = 2.0 kilobars Tangent modulus = 8.5 kilobars Maximum yield = 4.5 kilobars
Annealed Tantalum in 2.0 inch diameter bar	2.0 kilobars
Unannealed Tantalum in 0.5 inch bar	8.0 kilobars
Unannealed Tantalum in 0.75 inch bar	5.0 kilobars

SECTION II

INTRODUCTION

The Armor Defeat Mechanisms Technology Program at the Air Force Armament Laboratory is investigating means of explosively forming penetrators capable of defeating armored targets. Wave propagation computer programs, often referred to as hydrocodes, are being used in an iterative mode with experiments in an attempt to understand the basic physics of the slug forming and penetration processes. These codes are highly accurate given valid material property information. In particular, the codes require accurate uniaxial stress curves from initial elastic loading through failure. The AFATL is taking steps to provide such information as a function of temperature and at strain rates of interest (10^4 sec^{-1}) through programs involving the use of Hopkinson bars. However, these efforts are just getting underway, and will not provide data for several months.

Slow speed cylinder impact tests were conducted to provide some interim data. The experiments were conducted by Mr Leonard Wilson, Munitions Division, and personnel of the Guns, Rockets and Explosives Division. The cylinders were 0.3 inch diameter and 1 inch long and were fired at velocities from 250 to 625 fps against an extremely hard steel plate.

This report will discuss the calculational effort involved in reducing the experimental data to yield strength estimates.

SECTION III

COPPER RESULTS

Cylinders from three copper stocks were fired by Mr Wilson into a rigid steel target. The copper specimens were from a 4.5 inch diameter bar of dead soft Electrolytic Tough Pitch (ETP) Copper, and 0.75 and 1.0 inch bar stocks of unknown initial hardness ETP Copper. The specimens were fired in annealed and unannealed states.[1] The annealing process consisted of elevating the copper temperature to 600°F for one hour, followed by air cooling.

The primary copper of interest was the 4.5 inch diameter annealed stock. Figure 1 shows the results of an AFATL TOODY[2] two dimensional Lagrangian code calculation of the impact of this copper at 625 fps. The plot shows the final TOODY grid with experimental points in the circles. The upper plot is amplified in the radial (Z) direction. Only one half of the cylinder was run since the X axis is an axis of rotational symmetry. The fit in this run provided an initial yield point of 1.2 kilobars and a tangent modulus of 8.5 kilobars up to a maximum yield point at a strain of 38%.

There is some coupling of effects, but, in general, it was found that the final cylinder length was controlled by the initial yield point, the final cylinder radius was controlled by the maximum yield point and the extent of the central radial bulge was controlled by the tangent modulus. (It will be shown in the Tantalum analysis

(1) Annealing refers to heating performed at the AFATL. Unspecified annealing was probably performed by the manufacturer.

(2) AFATL-DLJW-HC-TN 77-2, "AFATL TOODY User's Guide", John J Osborn, Feb 77.

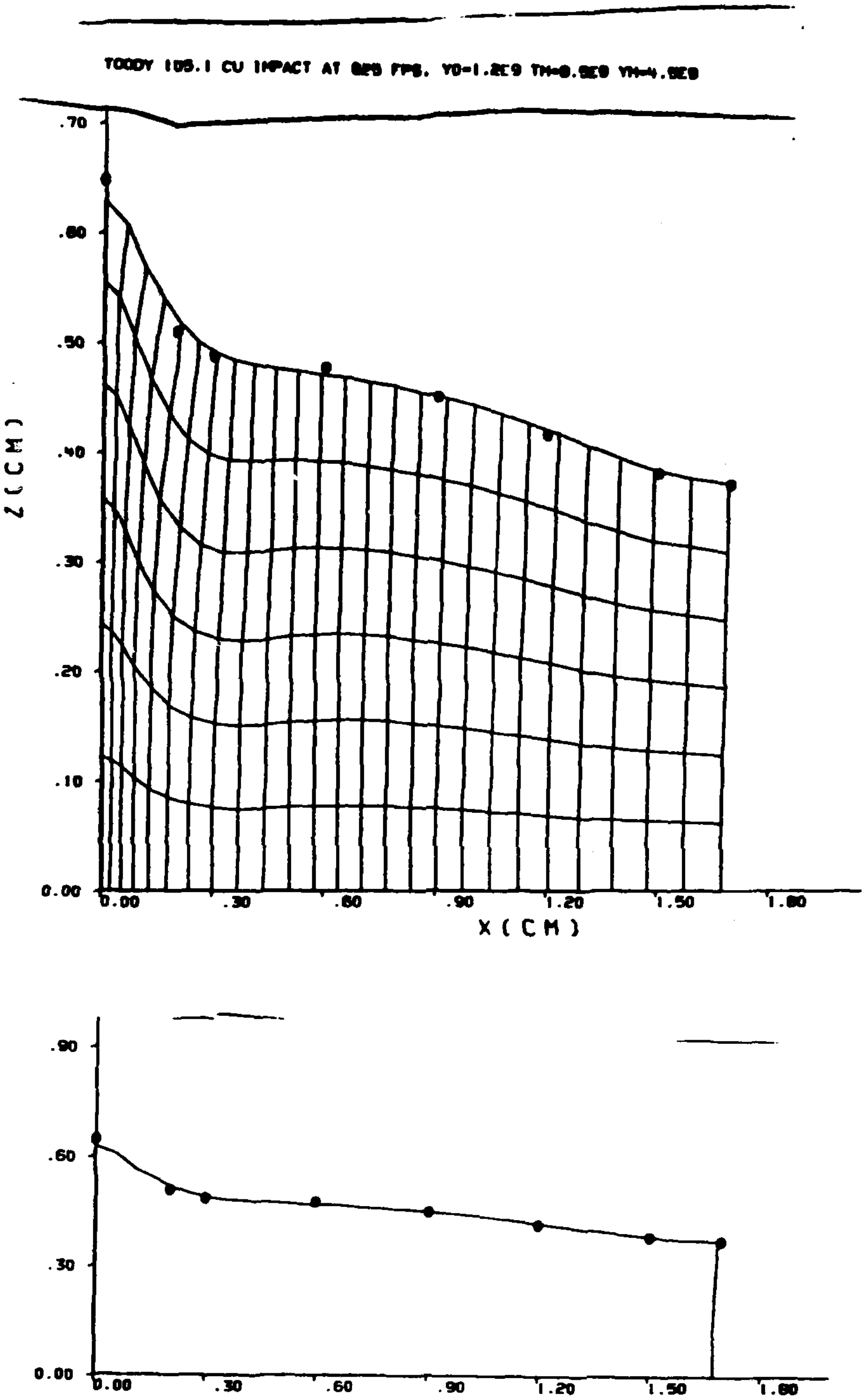


Figure 1

section that a constant yield strength model does not produce a bulged region).

Figure 2 demonstrates the sensitivity of the final radius to the maximum yield point. The radially distorted plots are for maximum yield points of 4.0 and 5.0 kilobars. The 5.0 kilobar model significantly underpredicts the radius. The 4.5 kilobar model is slightly under the experimental data for final radius. However, the sample had very small radially oriented cracks in the outer most portion of the deformed section and these cracks contributed to a flattening which the calculation cannot reproduce. With this in mind, it was judged that the 4.5 kilobar fit was best.

Figures 3 and 4 plot specific internal energy and strain components within the cylinder at the final problem time of 150 microseconds. The data is provided for each radial row of zones as a function of axial distance (X). The outermost row is the one labelled with a "2" and the innermost (along the axis) is labelled with a "7". Figure 3 shows that internal energy, computed from both hydrostatic and deviatoric work, was quite low. The peak in the grid is 6.57×10^8 ergs/gram - based on a value of zero prior to impact. The temperature rise expected from this energy value is less than 200°C. A more average energy value for the entire cylinder is approximately 1.5×10^8 ergs/gram, which means that the average temperature rise is less than 40°C. Therefore, the yield strength data generated from the experiment is essentially that at room temperature. The maximum axial strain (EXX) is a compressive 131%. There is very little shear strain (EXZ) involved.

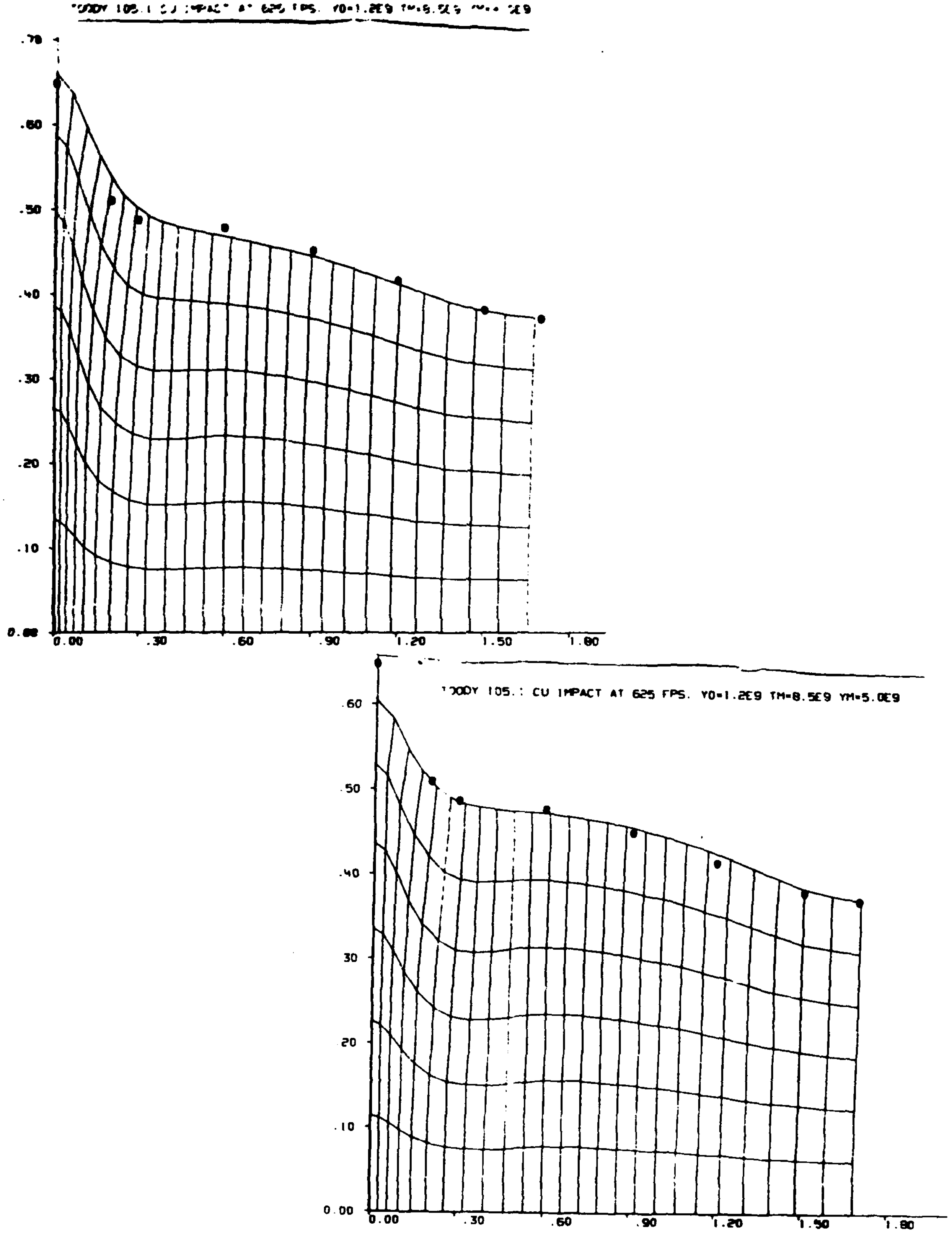

TOODY 105.1 CU IMPACT AT 625 FPS. YO=1.2E9 TM=8.5E9 YM=5.0E9
.70
.60
.50
.40
.30
.20
.10
0.00
0.00
.30
.60
.90
1.20
1.50
1.80
.60
.50
.40
30
20
.10
0.00
0.00
.30
.60
.90
1.20
1.50
1.80

Figure 2

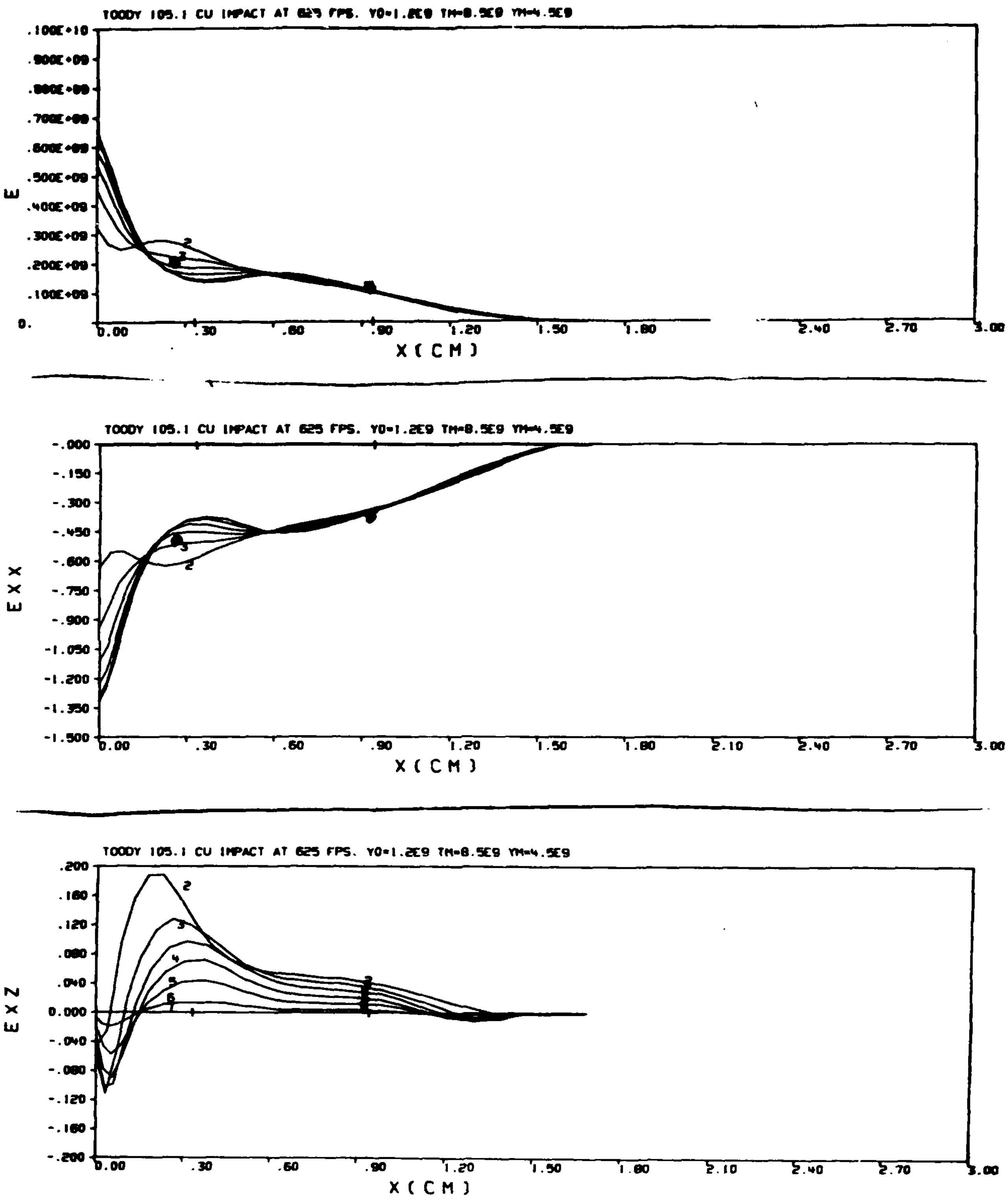
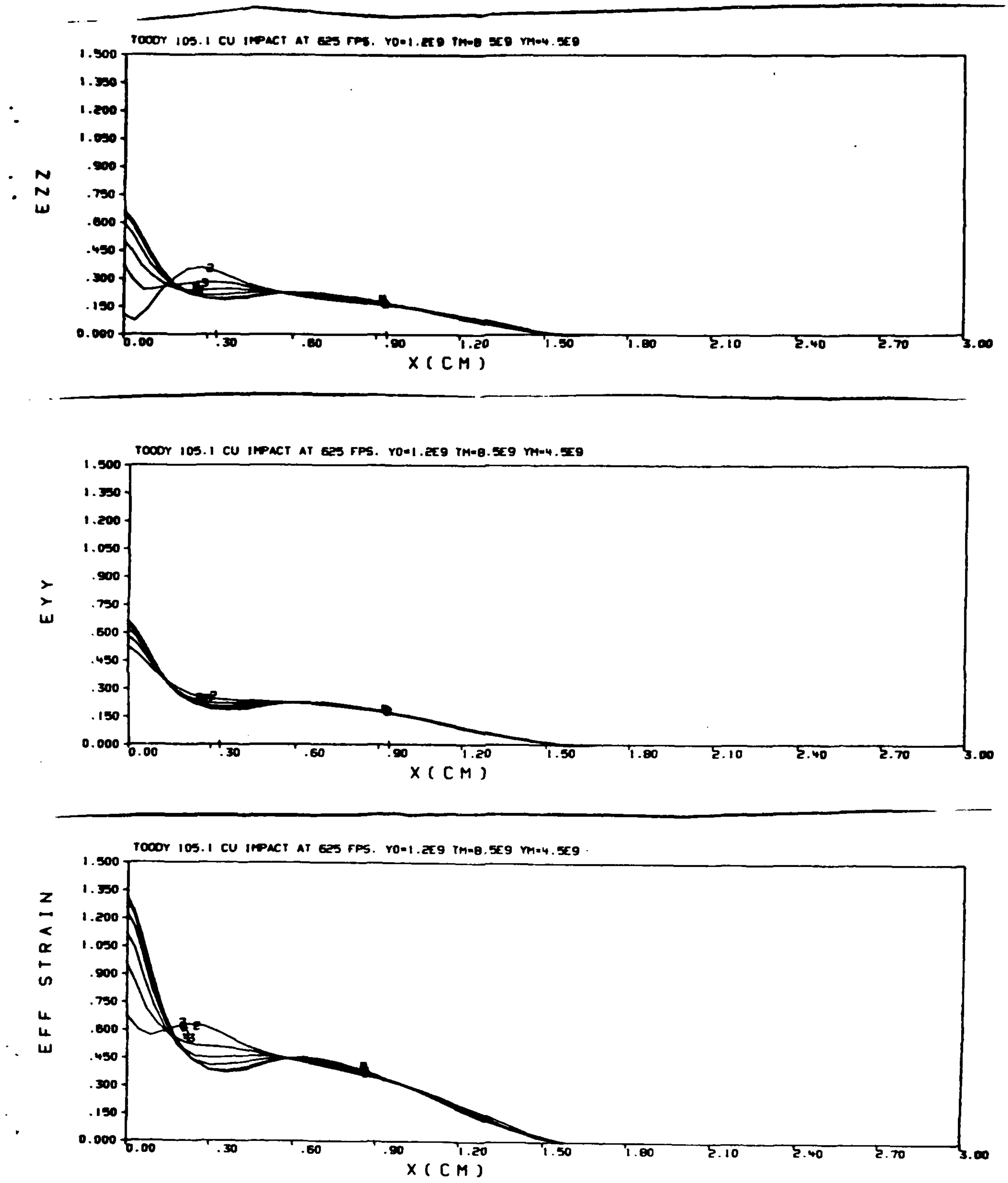

TOODY 105.1 CU IMPACT AT 625 FPS. YO=1.2E9 TM=8.5E9 YM=4.5E9
E
.100E+10
.900E+09
.800E+09
.700E+09
.600E+09
.500E+09
.400E+09
.300E+09
.200E+09
.100E+09
0.
0.00
.30
.60
.90
1.20
1.50
1.80
2.40
2.70
3.00
X (C M)
TOODY 105.1 CU IMPACT AT 625 FPS. YO=1.2E9 TM=8.5E9 YM=4.5E9
E X X
-.000
-.150
-.300
-.450
-.600
-.750
-.900
-1.050
-1.200
-1.350
-1.500
0.00
.30
.60
.90
1.20
1.50
1.80
2.10
2.40
2.70
3.00
X (C M)
TOODY 105.1 CU IMPACT AT 625 FPS. YO=1.2E9 TM=8.5E9 YM=4.5E9
E X Z
.200
.160
.120
.080
.040
0.000
-.040
-.080
-.120
-.160
-.200
0.00
.30
.60
.90
1.20
1.50
1.80
2.10
2.40
2.70
3.00
X (C M)

Figure 3



TOODY 105.1 CU IMPACT AT 625 FPS. YO=1.2E9 TM=8.5E9 YM=4.5E9
EZZ
EYY
EFF STRAIN
X (C M)

Figure 4

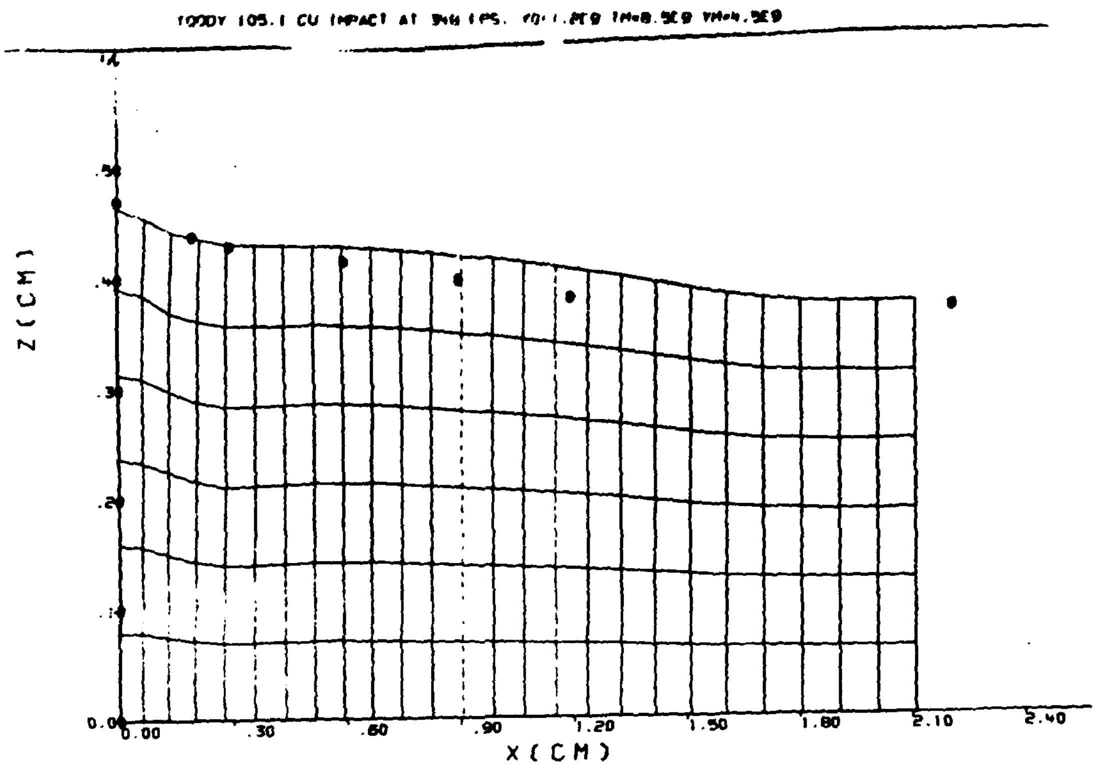
The radial strain (EZZ) is tensile and reaches 67% in the center of the cylinder and 13% at the outer radial points. The hoop strain (EYY) is also tensile and reaches a maximum of 67%. The effective strain, defined by

$$\text{Eff Strain} = \left(\frac{2}{9}\left[(EXX - EYY)^2 + (EXX - EZZ)^2 + (EYY - EZZ)^2 + 1.5EXZ^2\right]\right)^{1/2}$$

is tensile and reaches a peak of 130% along the cylinder axis. Sectioning of the cylinder showed that it did not fracture at these strain levels.

Figure 5 shows fits for a copper cylinder from the annealed 0.75 inch diameter stock. Impact in this case was at 348 fps. The upper plot is a radially amplified view of the calculation and experimental results using the 4.5 inch diameter stock strength model. This model fails to duplicate either the final cylinder length or the radial bulge. The lower plot in the figure shows the effect of simply increasing the initial yield strength to 2 kilobars. It is almost a perfect fit. The tangent modulus should be changed very slightly to obtain an exact fit. The calculation indicates that the two copper stocks have essentially the same yield curves with the exception of the initial point. This is consistent with an hypothesis that the two copper stocks are identical with the exception of work introduced in the forming process.

Specific calculations for the 1 inch bar stock and the unannealed 0.75 inch bar stock were not undertaken. Plots of final diameter and length vs velocity were constructed and it was determined that the


TOODY 105.1 CU IMPACT AT
Z (C M)
.50
.40
.30
.20
.10
0.00
0.00
.30
.60
.90
1.20
1.50
1.80
2.10
2.40
X (C M)

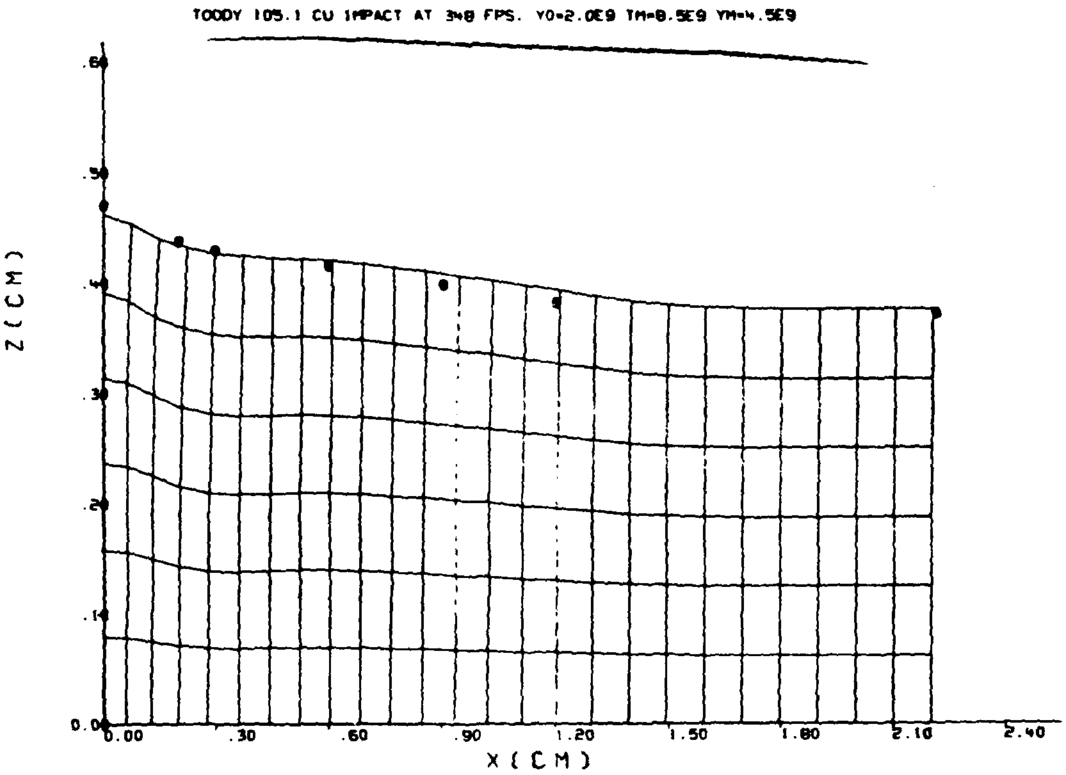

TOODY 105.1 CU IMPACT AT 348 FPS. YO=2.0E9 TM=8.5E9 YM=4.5E9
Z (C M)
.60
.50
.40
.30
.20
.10
0.00
0.00
.30
.60
.90
1.20
1.50
1.80
2.10
2.40
X (C M)

Figure 5

previous two models adequately describe all of the cases within the observed experimental error. That is, the smaller bar stocks have the same yield strength curve whether annealed or unannealed.

SECTION IV

TANTALUM RESULTS

Samples from three Tantalum bars were fired at velocities in the range of 400 to 500 fps. The bars were unannealed 0.5 inch diameter and 0.75 inch diameter stocks and an annealed 2 inch diameter stock.(3)

Figure 6 shows a comparison between calculation and experiment for the 0.5 inch stock fired at 463 fps. The only experimental points shown are final radius (0.6 cm) and final length (2.17 cm), since for a non-work hardening material these adequately determine yield strength. The result of the calculation was that the material could be modelled with a constant yield strength of 8 kilobars. Figure 7 shows the same impact at 7 and 9 kilobars. It can be seen that 8 kilobars does provide the best fit of the three.

Figures 8 and 9 provide specific internal energy and strain components at the final calculational time of 150 microseconds. Internal energy is seen again to be very low. The peak strains are quite similar to those seen in the 625 fps copper impact.

Figure 10 shows a 5 kilobar constant yield strength fit to the experimental data for a sample from the 0.75 inch stock fired at 406 fps. The fit could possibly be improved upon slightly by raising the yield strength a fraction of a kilobar. Figures 11 and 12 present specific internal energy and strain component predictions for this case. The maximum effective strain reaches 150% for this impact - with no

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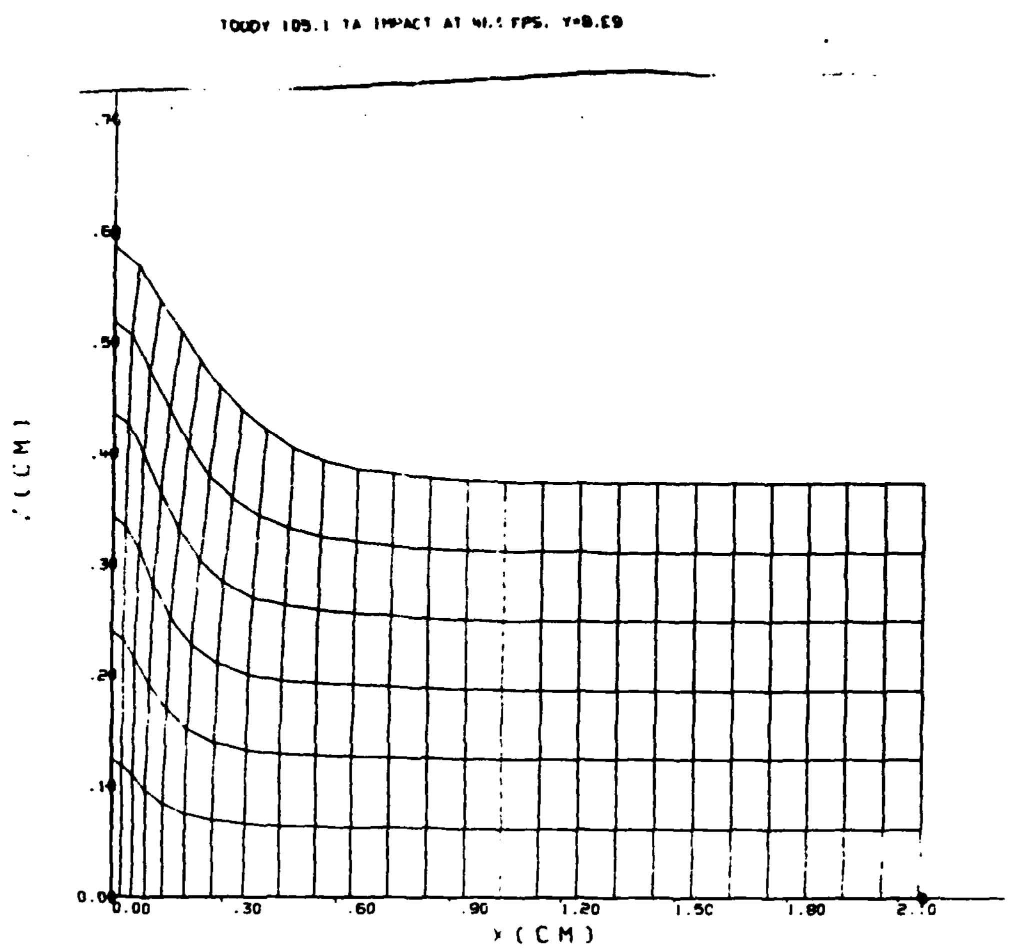
(3) Annealing here refers only to annealing performed by the Manufacturer. The annealing process was not specified.


TOODY 105.1 TA IMPACT AT
0.00
.30
.60
.90
1.20
1.50
1.80
X (CM)

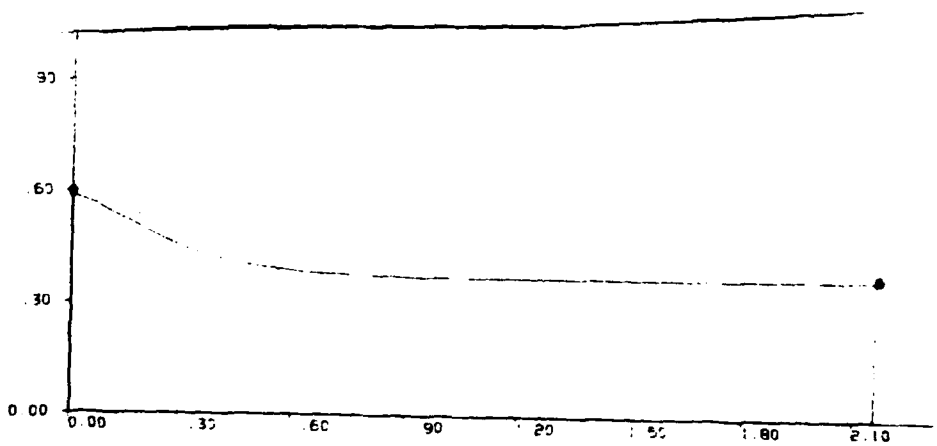

.60
.30
0.00
0.00
.60
90
1.80
2.10

Figure 6

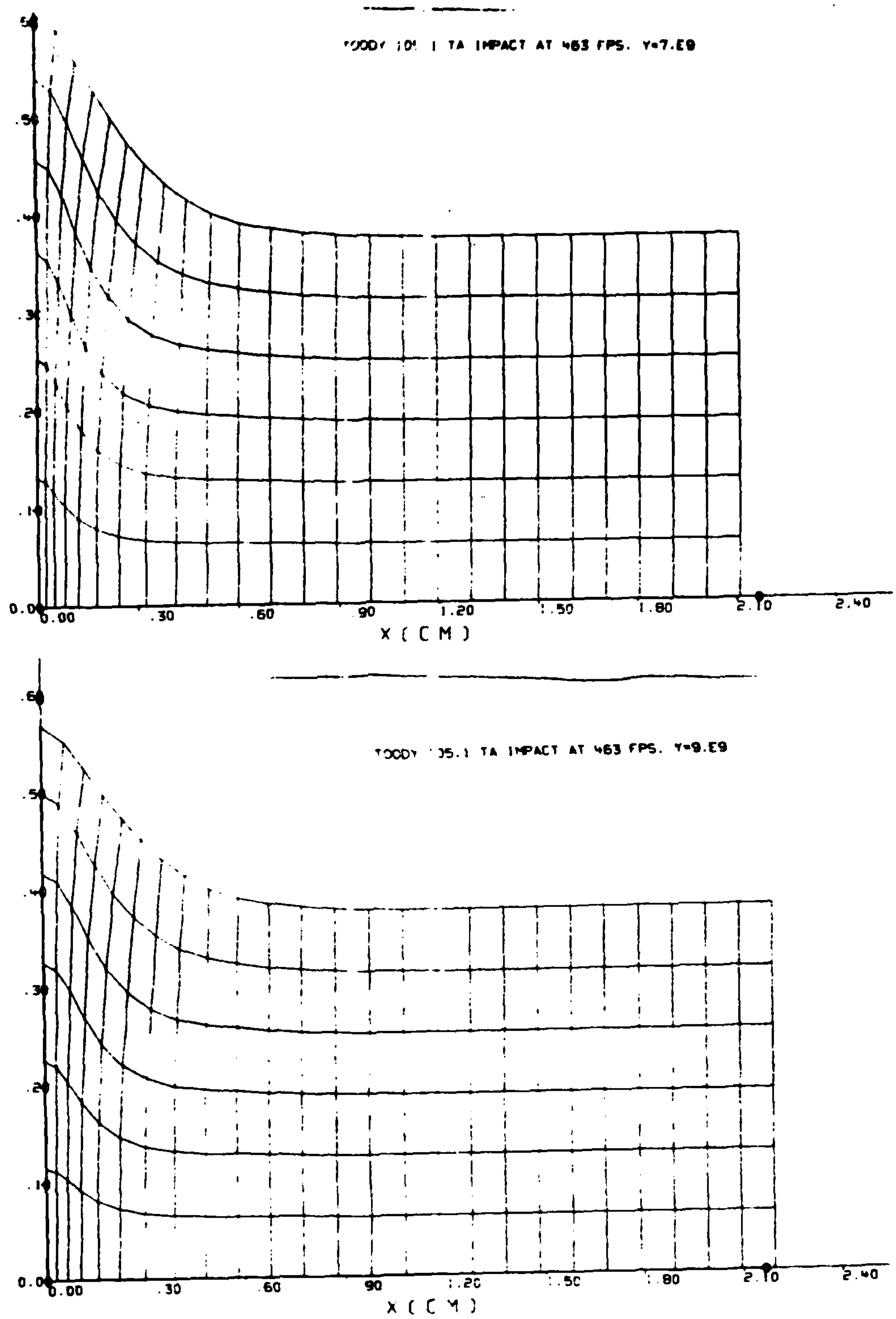

TOODY 105.1 TA IMPACT AT 463 FPS. Y=7.E9
Z (C M)
X (C M)
TOODY 105.1 TA IMPACT AT 463 FPS. Y=9.E9
Z (C M)
X (C M)

Figure 7

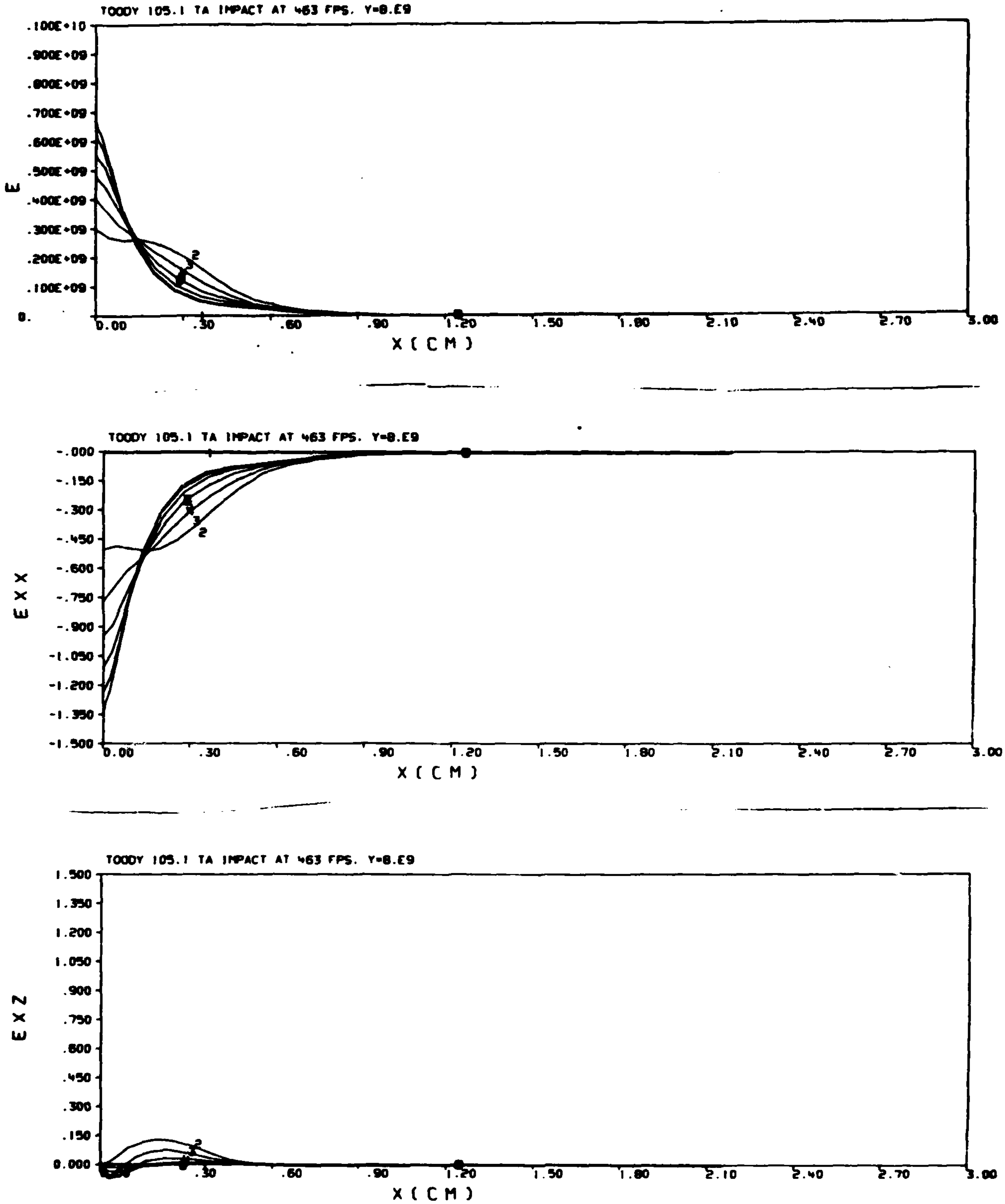

TOODY 105.1 TA IMPACT AT 463 FPS. Y=8.E9
.100E+10
.900E+09
.800E+09
.700E+09
.600E+09
.500E+09
.400E+09
.300E+09
.200E+09
.100E+09
0.
E
0.00
.30
.60
.90
1.20
1.50
1.80
2.10
2.40
2.70
3.00
X (C M)
TOODY 105.1 TA IMPACT AT 463 FPS. Y=8.E9
-.000
-.150
-.300
-.450
-.600
-.750
-.900
-1.050
-1.200
-1.350
-1.500
E X X
0.00
.30
.60
.90
1.20
1.50
1.80
2.10
2.40
2.70
3.00
X (C M)
TOODY 105.1 TA IMPACT AT 463 FPS. Y=8.E9
1.500
1.350
1.200
1.050
.900
.750
.600
.450
.300
.150
0.000
E X Z
.30
.60
.90
1.20
1.50
1.80
2.10
2.40
2.70
3.00
X (C M)

Figure 8

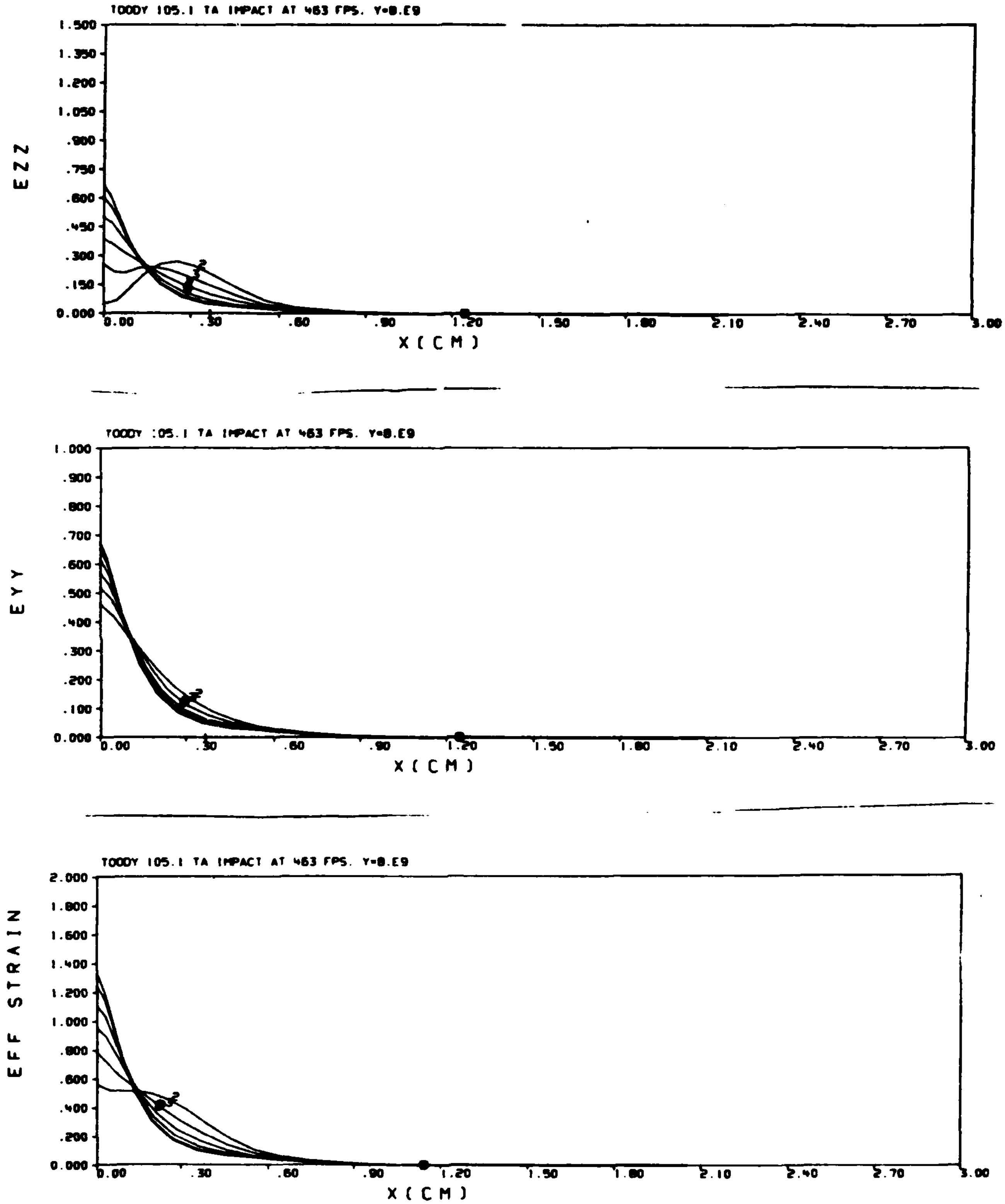

TOODY 105.1 TA IMPACT AT 463 FPS. Y=8.E9
EZZ
X (C M)
TOODY 105.1 TA IMPACT AT 463 FPS. Y=8.E9
EYY
X (C M)
TOODY 105.1 TA IMPACT AT 463 FPS. Y=8.E9
EFF STRAIN
X (C M)

Figure 9

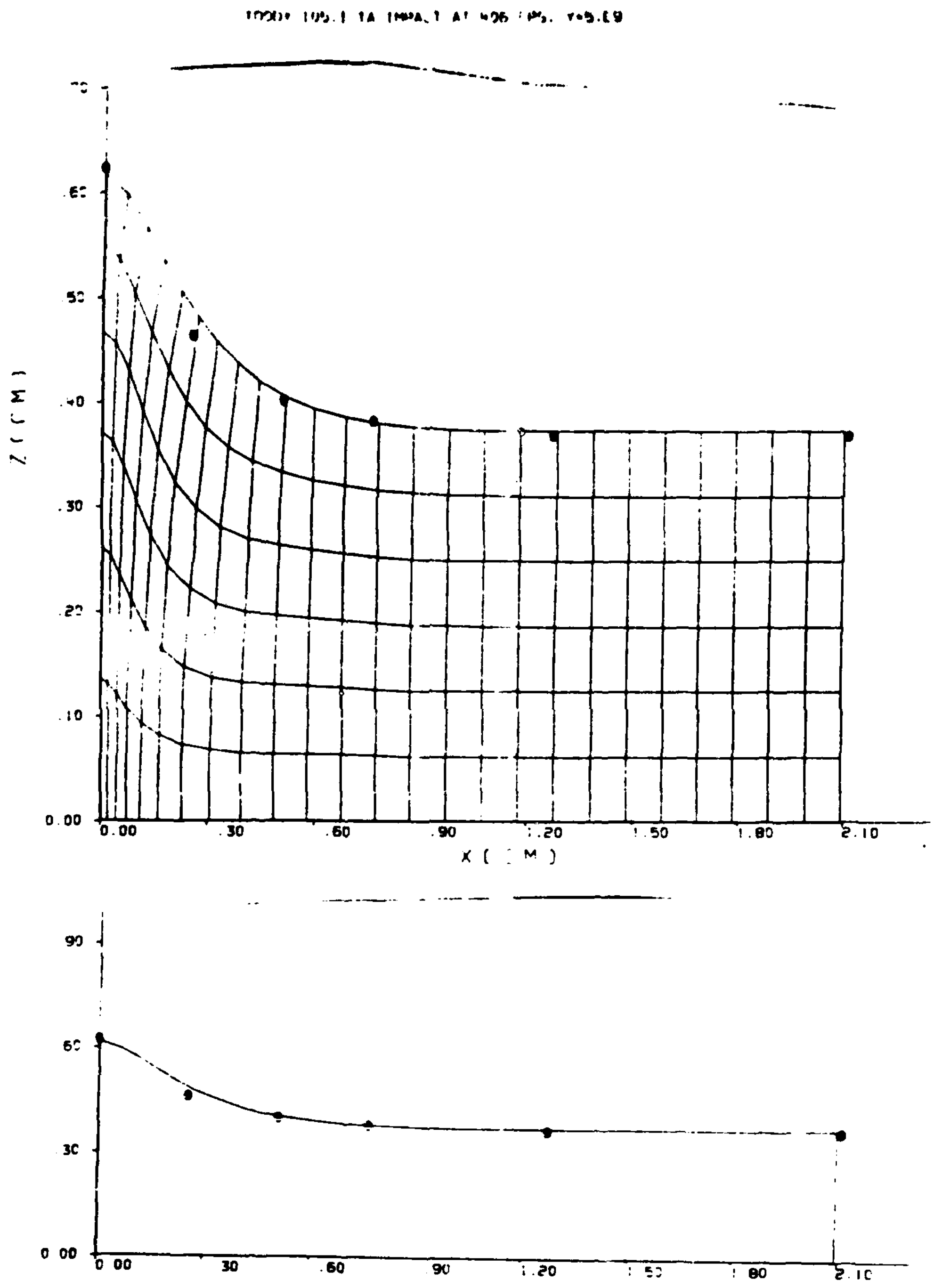


Figure 10

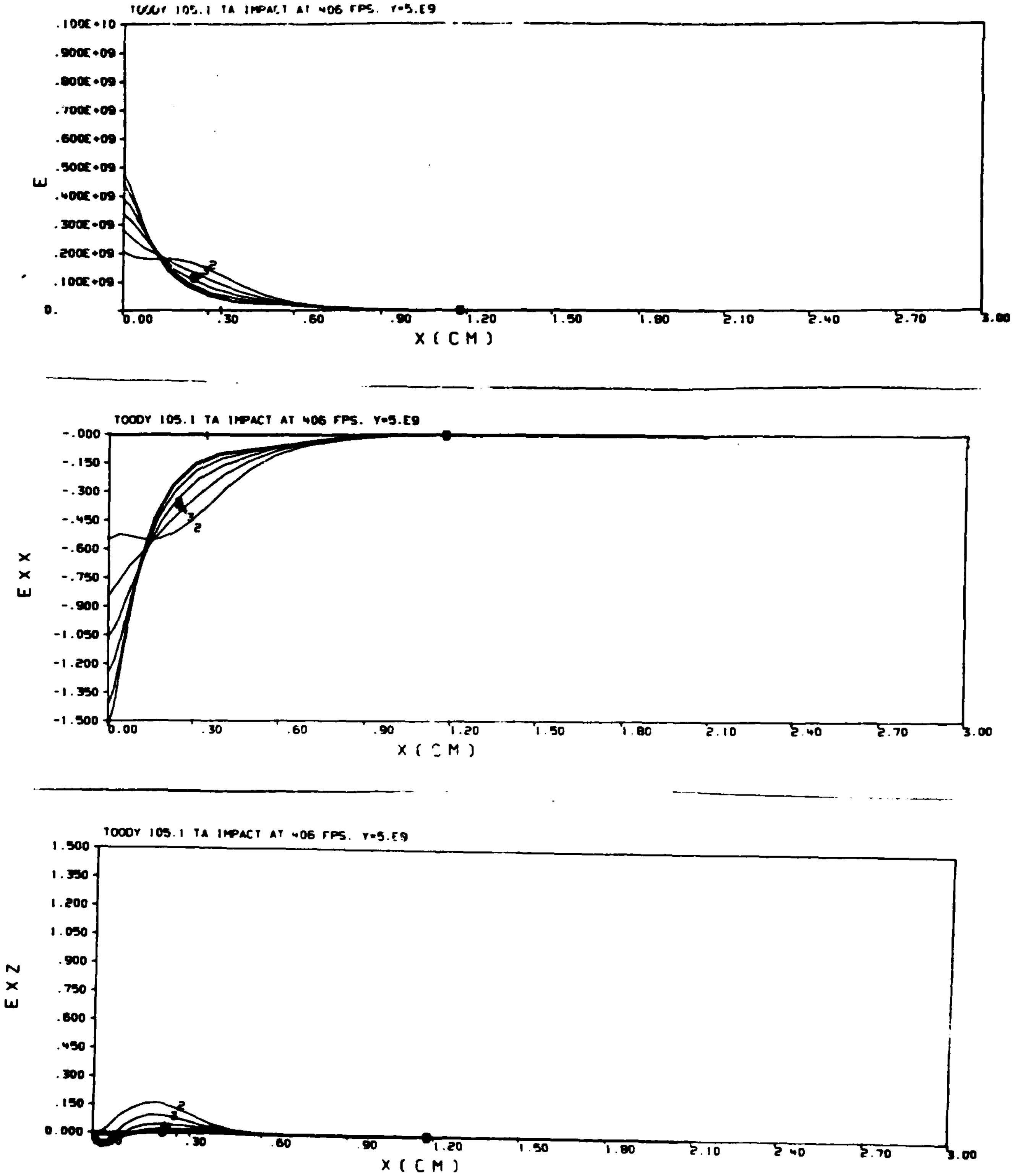
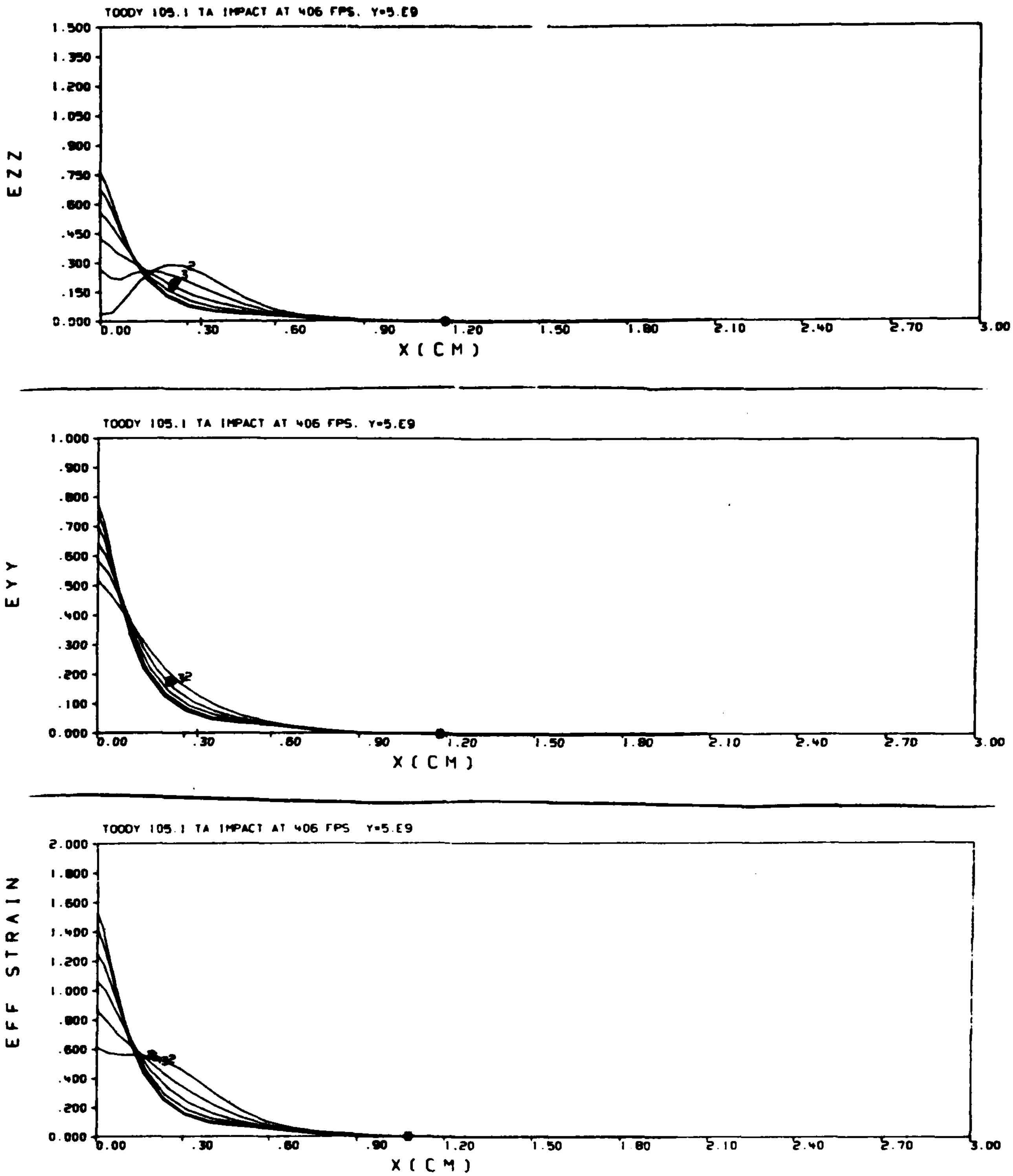

TOODY 105.1 TA IMPACT AT 406 FPS. Y=5.E9
E
.100E+10
.900E+09
.800E+09
.700E+09
.600E+09
.500E+09
.400E+09
.300E+09
.200E+09
.100E+09
0.
0.00
.30
.60
.90
1.20
1.50
1.80
2.10
2.40
2.70
3.00
X (C M)
TOODY 105.1 TA IMPACT AT 406 FPS. Y=5.E9
EXX
-.000
-.150
-.300
-.450
-.600
-.750
-.900
-1.050
-1.200
-1.350
-1.500
X (C M)
TOODY 105.1 TA IMPACT AT 406 FPS. Y=5.E9
EXZ
1.500
1.350
1.200
1.050
.900
.750
.600
.450
.300
.150
0.000
X (C M)

Figure 11



TOODY 105.1 TA IMPACT AT 406 FPS. Y=5.E9
EZZ
X (C M)
TOODY 105.1 TA IMPACT AT 406 FPS. Y=5.E9
EYY
X (C M)
TOODY 105.1 TA IMPACT AT 406 FPS Y=5.E9
EFF STRAIN
X (C M)

Figure 12

observable fracture induced. It is not known why this Tantalum has a 5 kilobar yield strength while the 0.5 inch diameter stock yield strength is 8 kilobars. Available manufacturer's specifications show no difference in impurities or impurity levels and no annealing for either stock.

The 2.0 inch diameter annealed bar stock has not yet been fired in cylinder impact tests. It has, however, been used in extensive self forging liner tests designed to provide strength data. The tests were calculated using TOODY with constant yield strength models for the Tantalum.

Figure 13 shows TOODY material boundaries and zoning for one of these calculations. Note that the Z axis is an axis of rotational symmetry. Sliding surfaces exist between the liner and the explosive and the backplate and the explosive. The liner turns inside out and heads down range center first. Figure 14 presents TOODY results using a 2.0 kilobar yield strength along with tracings from x-rays taken during the tests. Both calculations and x-rays show the liners' final configurations. The calculations and x-rays are on different scales, but it is clear by comparing shapes that the constant yield strength value of 2.0 kilobars provides an excellent fit to all of the data. One 5.0 kilobar calculation is shown to give some indication of the sensitivity of the shape to the assumed strength level. The calculations for each test appear directly under the appropriate x-ray. The calculations provide a prediction of inner liner surface not seen in the x-ray. Since several thicknesses were fired, and 2.0 kilobars fit

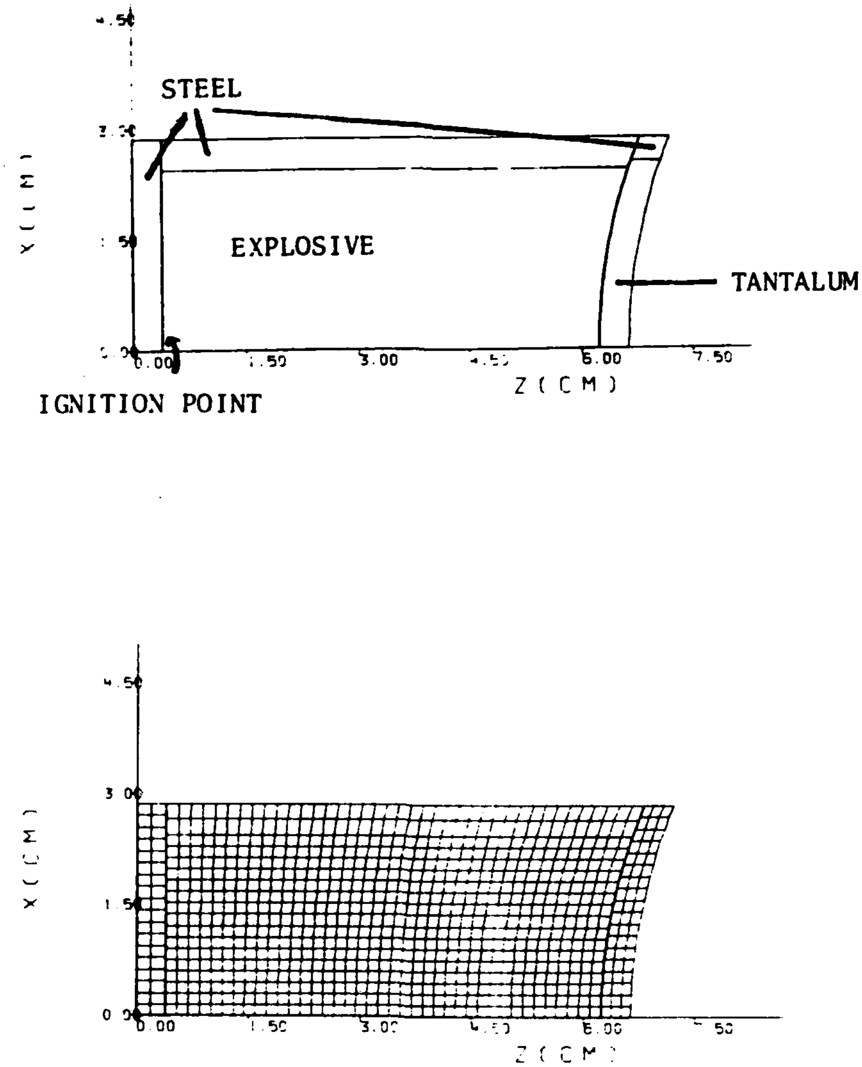
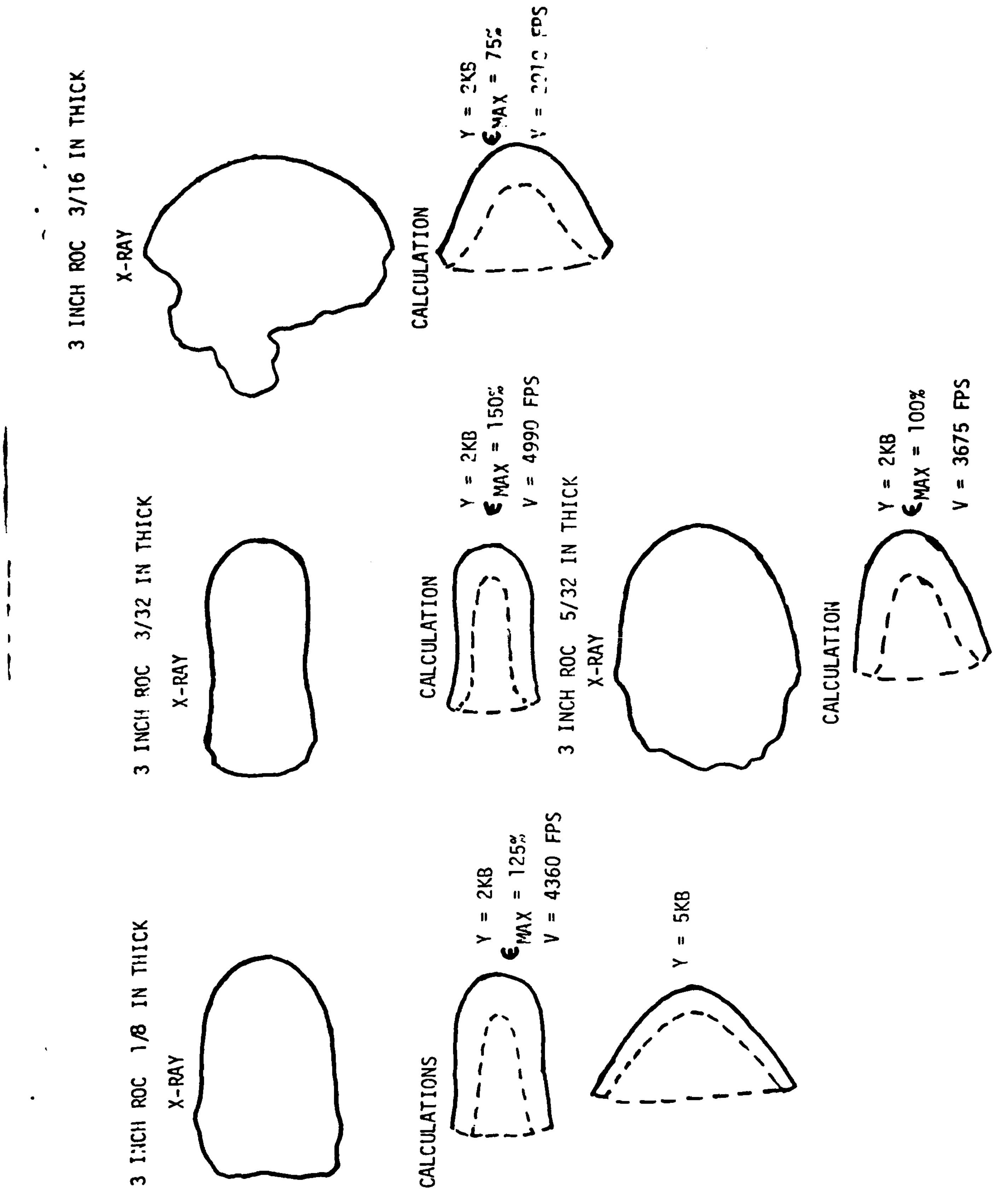


Figure 13



3 INCH ROC 3/16 IN THICK
X-RAY
CALCULATION
Y = 2KB
ϵ_{MAX} = 75%
3 INCH ROC 3/32 IN THICK
X-RAY
CALCULATION
Y = 2KB
ϵ_{MAX} = 150%
V = 4990 FPS
3 INCH ROC 5/32 IN THICK
X-RAY
CALCULATION
Y = 2KB
ϵ_{MAX} = 100%
V = 3675 FPS
3 INCH ROC 1/8 IN THICK
X-RAY
CALCULATIONS
Y = 2KB
ϵ_{MAX} = 125%
V = 4360 FPS
Y = 5KB

Figure 14

them all, it can be inferred that the Tantalum does not significantly work harden. Liner velocities and maximum tensile strains were predicted in the calculations. The Tantalum reached 150% strain with no evidence of failure.

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